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Model-Based Algorithms for Detecting Damage in Ultrasonic Nondestructive Evaluation Measurements

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Lawrence Livermore National Laboratory

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July 2, 2008

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Auspices and Disclaimer

Auspices

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Disclaimer

We Have an Interdisciplinary Team

- Graham Thomas - ENG/MMED
  - Project Management
  - NDE, materials characterization
- Chris Robbins - ENG/NSED
  - Program Management
  - Data acquisition, hardware, signal processing software, NDE
- Grace Clark - ENG/NSED
  - Image/signal processing, target/pattern recognition, sensor data fusion, NDE
- Katherine Wade - ENG/NSED
  - Signal processing software and testing

Agenda

- Introduction
  - The Damage Detection Problem
    - Ultrasonic NDE *(As-Built Modeling)*
    - Motivated by Time Domain Reflectometry for Cables
  - This is work in progress
- Technical Approach - *Model-Based Damage Detection*
- Damage Detection Processing Results
  - Ultrasonic NDE
  - TDR for Cables
- Discussion

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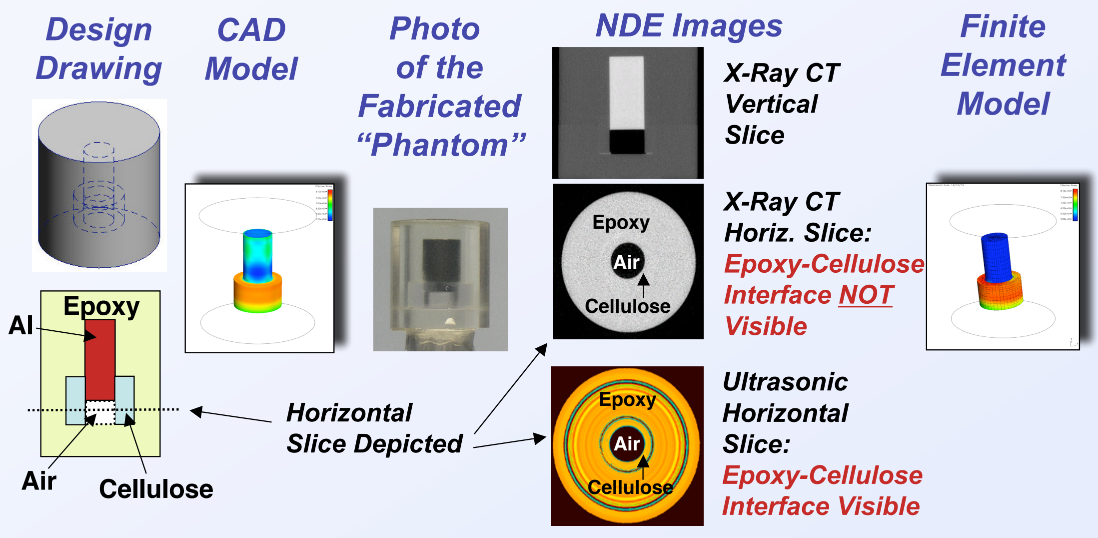
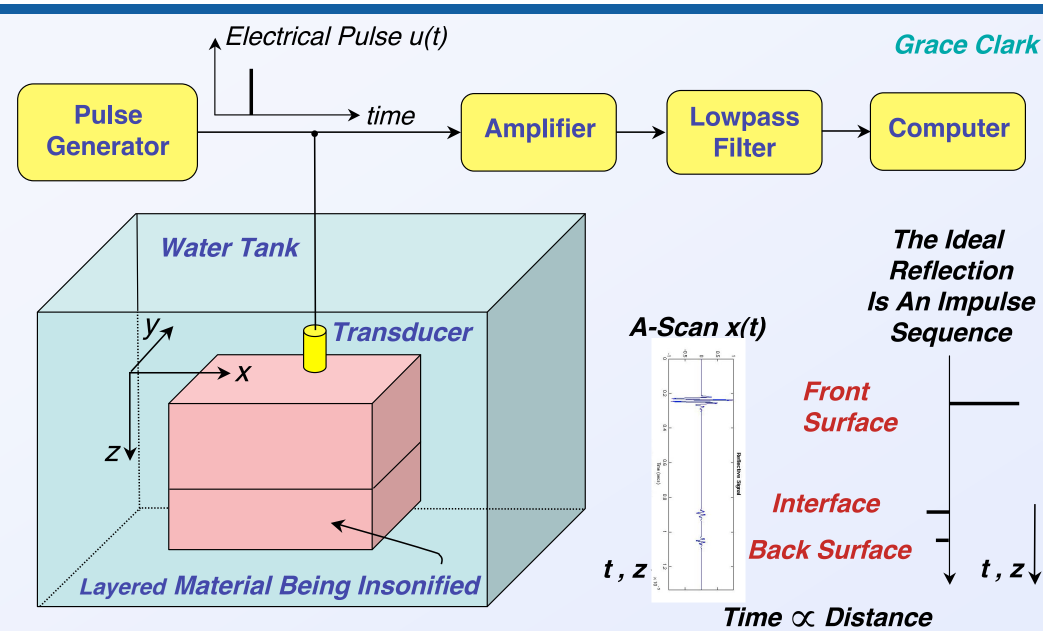
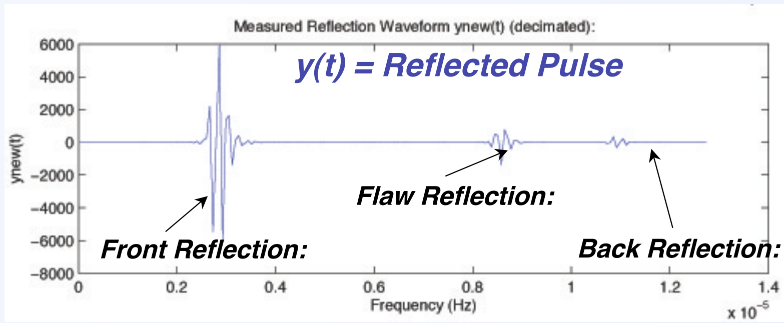
"As-Built Modeling" is Used to Compare Mechanical Objects: "As-Designed," "As-Built," "As Inspected After Use"

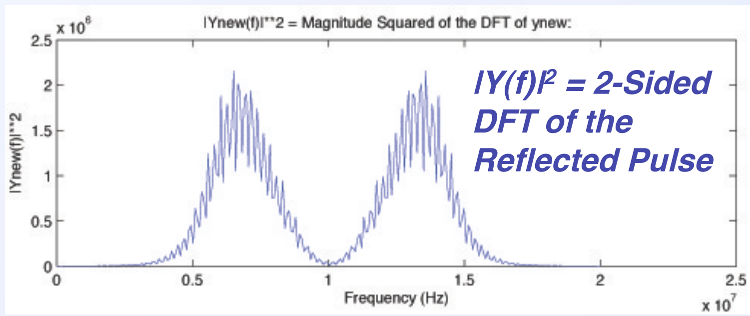


Ultrasonic Pulse-Echo Signals *(A-Scans)* Are *Distorted* By the *Transducer* and the *Propagation Paths ("Ringing")*



Ultrasonic Pulses Are *Bandlimited* by the Transducer ==> The Pulses *"Ring", Reducing Spatial Resolution*





We Define Ultrasonic *A-, B-, and C-Scans* Used in Nondestructive Evaluation (NDE) Studies:

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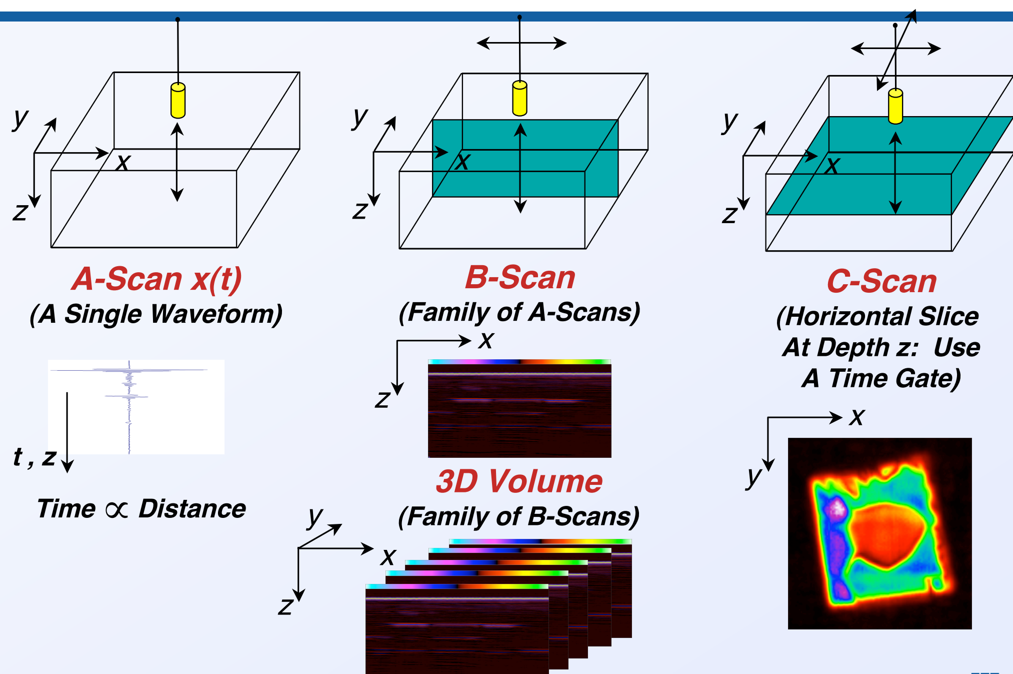
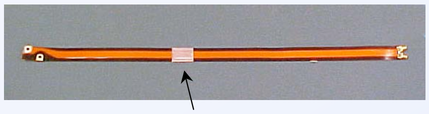


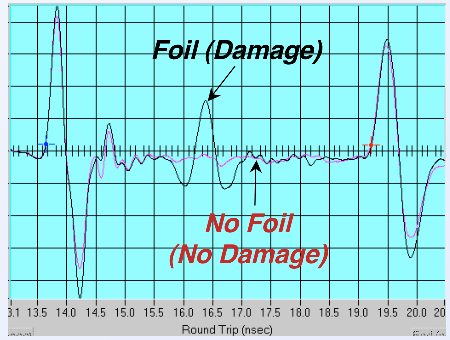
We Are Testing Two-Conductor Flat Cables With Kapton Insulation - For Dielectric Anomalies

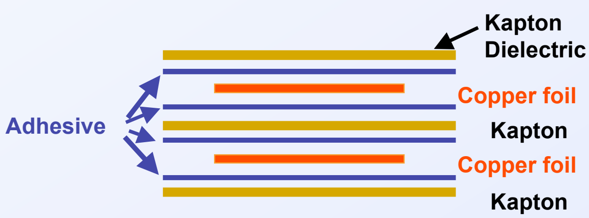
Red TDR Signal => Good Cable
Black TDR Signal => Damaged Cable

Two-Conductor Flat Cable With Kapton Insulation



Foil Simulating a Capacitive Discontinuity (Damage)





Expected Damage Types:
- *Compressions*
- *Punctures*
- *Short Circuits*
- *Open Circuits*

The Model-Based Damage Detection Approach:
Detect a Model Mismatch if Damage is Present

- **Exploit the fact that the measurements are reasonably repeatable.**

- **Build a forward model of the dynamic system (cable) for the case in which *NO DAMAGE* exists**

- **Whiteness Testing on the *Innovations (Errors):***
  Estimate the output of the actual system using measurements from a dynamic test.

  - If *no damage* exists, the model will match the measurements, so the "innovations" (errors) will be *statistically white*.

  - If a *damage* exists, the model will not match the measurements, so the "innovations" (errors) will *not be statistically white.*

- **Weighted Sum Square Residuals (WSSR) Test:**
  The WSSR provides a single metric for the model mismatch

Step #1: System Identification to Estimate the Dynamic Model of the *Undamaged Cable*

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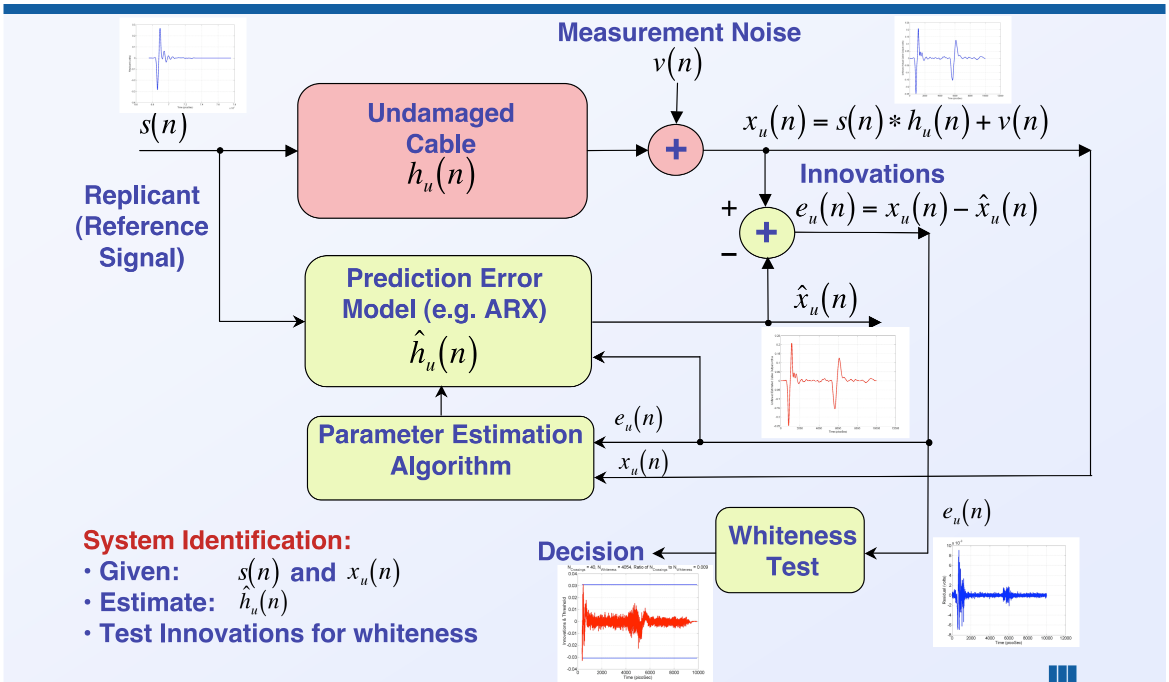
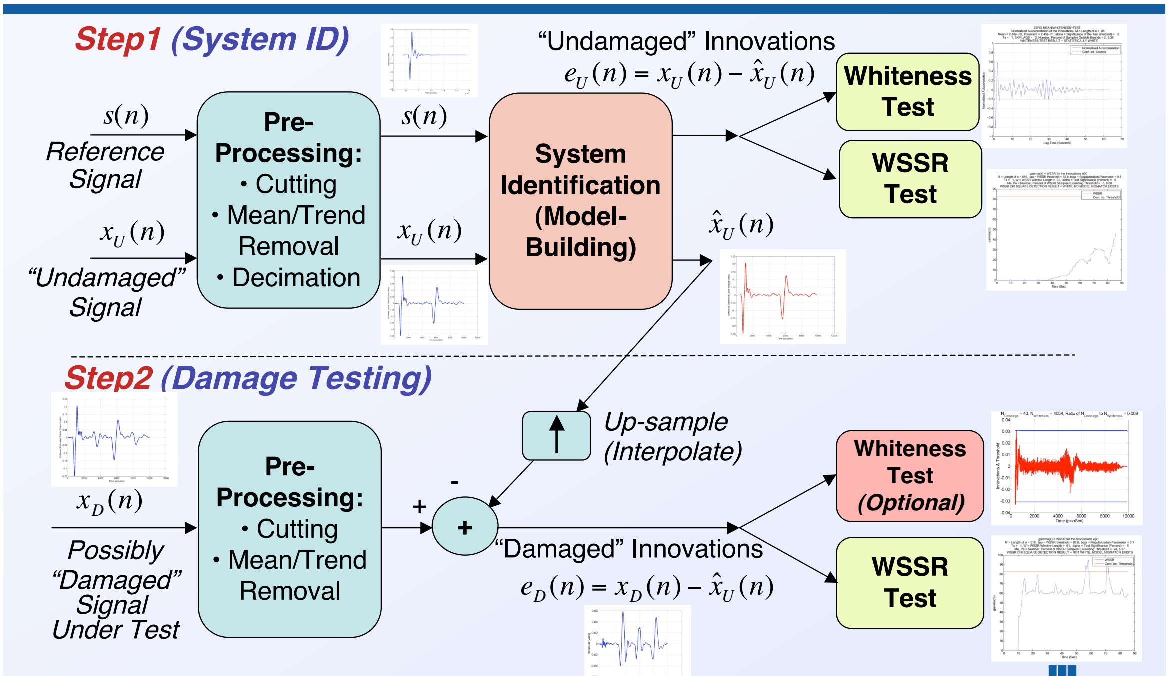


System Identification:
- Given: $s(n)$ and $x_u(n)$
- Estimate: $\hat{h}_u(n)$
- Test Innovations for whiteness

Step1 (System ID) is Done *"Offline"*
Step2 (Damage Testing) is Done *"Online"*



The Form of the Linear System Model is "ARX" = "Auto-Regressive with Exogenous Input"

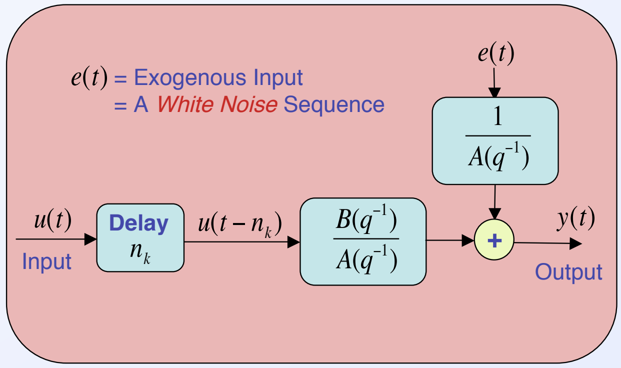
$$y(t) = \frac{B(q^{-1})}{A(q^{-1})} u(t-nk) + \frac{1}{A(q^{-1})} e(t)$$

Where:

$$A(z) = 1 + a_1 q^{-1} + a_2 q^{-2} \cdots + a_{N_a} q^{-N_a}$$

$$B(z) = b_0 + b_1 q^{-1} + b_2 q^{-2} \cdots + b_{N_b} q^{-N_b}$$

q^{-1} = Delay Operator



The model parameters are estimated using a least squares algorithm.

- Solve an over-determined set of linear equations
- Solve using QR factorization algorithm
- The regression matrix is formed so that only measured quantities are used (no fill-out with zeros).

Scalar WSSR (Weighted Sum Squared Residuals) Test

For a Scalar Measurement (p = 1)

Given the innovations signal $e(n)$

We define the scalar WSSR test statistic at time index n:

$$\gamma(n) = \sum_{j=n-W+1}^{n} \frac{e^2(j)}{V(j)}, \quad \text{for } n \geq W$$

Note: We estimate WSSR over a finite sliding window of length W samples.

Where:

$$V(n) = \frac{1}{W} \sum_{j=n-W+1}^{n} \left[e^2(j) - \bar{e}(j) \right]^2, \quad \text{for } n \geq W$$

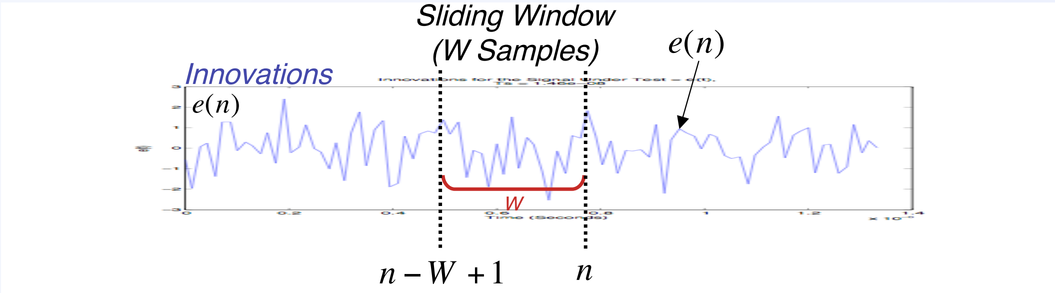
Sample variance over the sliding window

$$\bar{e}(n) = \frac{1}{W} \sum_{j=n-W+1}^{n} e(j), \quad \text{for } n \geq W$$

Sample mean over the sliding window

Scalar WSSR is Calculated Using a Sliding Window Over the Innovations Sequence $e(n)$

WSSR = "Weighted Sum Squared Residuals"



$$\gamma(n) = \sum_{j=n-W+1}^{n} \frac{e^2(j)}{V(j)}, \quad \text{for } n \geq W$$

WSSR is a useful test statistic for detecting an abrupt change, or "jump" in the innovations

Define the WSSR Hypothesis Test

By defining a threshold (later), the WSSR test becomes:

$$\text{If } \gamma(n) \underset{< H_0}{\overset{\geq H_1}{}} \tau \quad , \qquad (\tau = \text{Decision Threshold})$$

Read this as follows:

$$\text{If } \gamma(n) \geq \tau, \text{ then } H_1 \text{ is true}$$
$$\text{If } \gamma(n) < \tau, \text{ then } H_0 \text{ is true}$$

WSSR Test

For a scalar measurement (p = 1) *(Continued)*

For the null hypothesis H_0, the WSSR is chi square distributed:

$$\gamma(n) \sim \chi^2(W)$$

However, for W > 30, the WSSR is approximately normally distributed:

$$\gamma(n) \sim N(W, 2W)$$

At the significance level α , the probability of rejecting the null Hypothesis (detecting a jump) is:

$$P\left(\left|\frac{\gamma(n) - W}{\sqrt{2W}}\right| > \left|\frac{\tau - W}{\sqrt{2W}}\right|\right) = \alpha$$

WSSR Hypothesis Test (Continued)

At the significance level α , we can create a confidence interval test:

For H_0: $P\left[\gamma(n) < \tau\right] = 1 - \alpha = .95$

For H_1: $P\left[\gamma(n) \geq \tau\right] = \alpha = .05$

For a significance level $\alpha = .05$, the threshold is:

$$\tau = W + 1.96\sqrt{2W}$$

The Scalar WSSR Confidence Interval Threshold is Parameterized by *the Window Length W*

Summary of the WSSR Test for Significance $\alpha = .05$:

$$\gamma(n) = \sum_{j=n-W+1}^{n} \frac{e^2(j)}{V(j)}, \quad \text{for } n \geq W$$

$$V(n) = \frac{1}{W} \sum_{j=n-W+1}^{n} \left[e^2(j) - \bar{e}(j)\right]^2, \quad \text{for } n \geq W$$

$$\bar{e}(n) = \frac{1}{W} \sum_{j=n-W+1}^{n} e(j), \quad \text{for } n \geq W$$

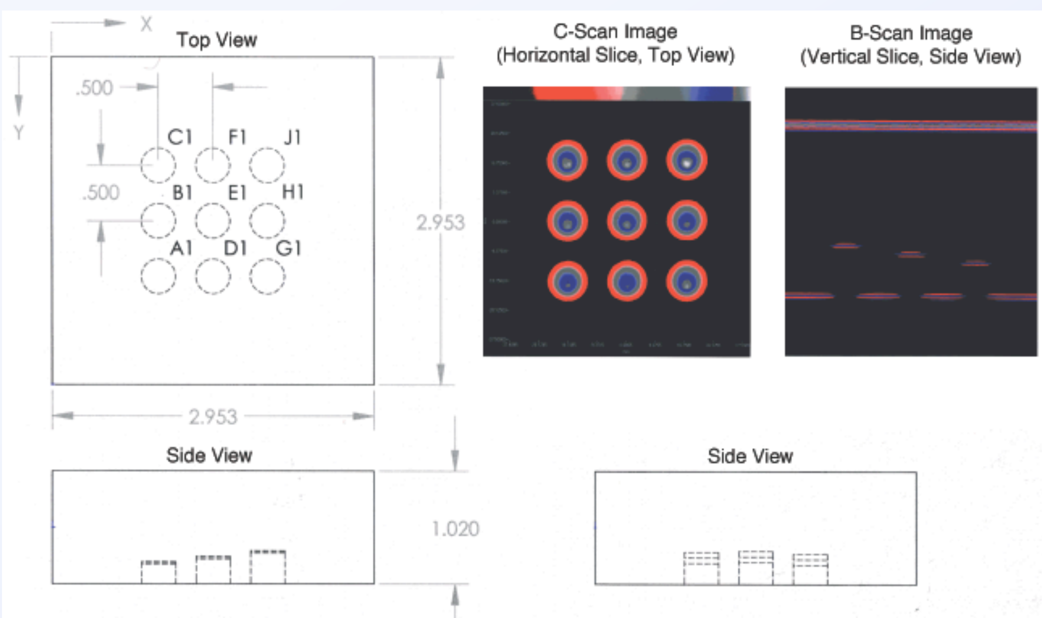
$$\tau = W + 1.96\sqrt{2W}$$

$$\text{If } \gamma(n) \underset{< H_0}{\overset{\geq H_1}{}} \tau \quad , \quad (\tau = \text{Decision Threshold})$$

In practice, we implement the WSSR test as follows:

- Let F_E = Fraction of samples of $\gamma(n)$ that exceed the threshold
- If $F_E \leq \alpha$, Declare H_0 is true (innovations are white, no jump)
- If $F_E > \alpha$, Declare H_1 is true (innovations are not white, jump)

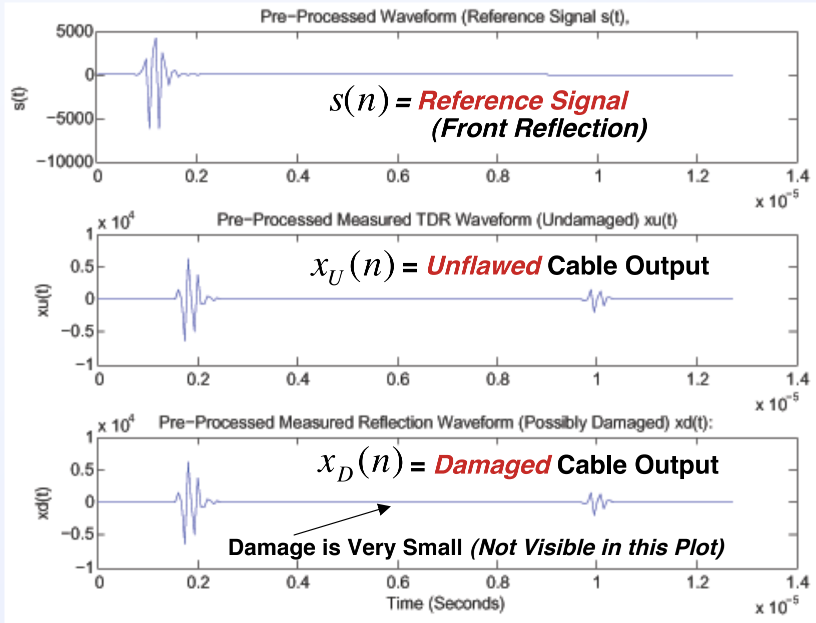
We Constructed a "Phantom" Part - *Aluminum Block* Containing *Flat-Bottom Holes*



UT1a_s_xu_xdC.pdf

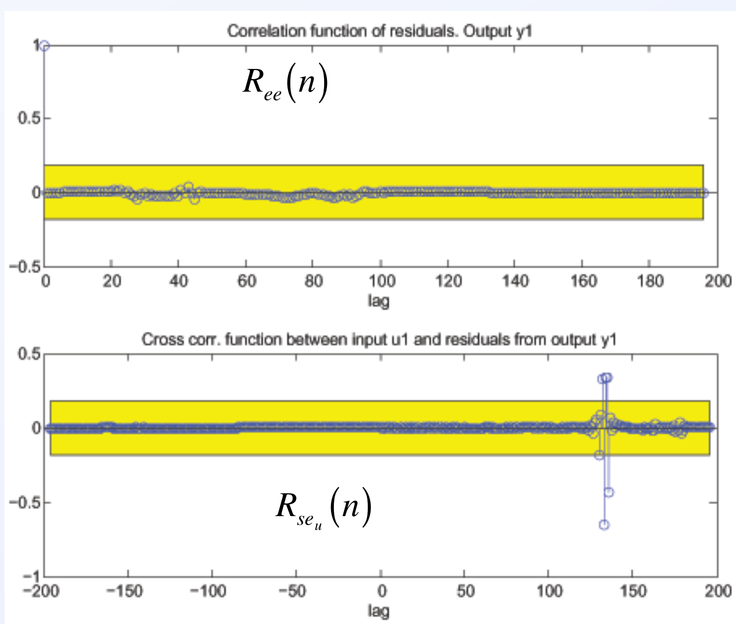
System Identification: Preprocessed Signals

$f_s = 1.0e8\ Hz$
$T_s = 1.0e-8\ \sec$



UT1_Ree_RsxuC.pdf

System Identification: *Correlation Tests are Satisfactory*

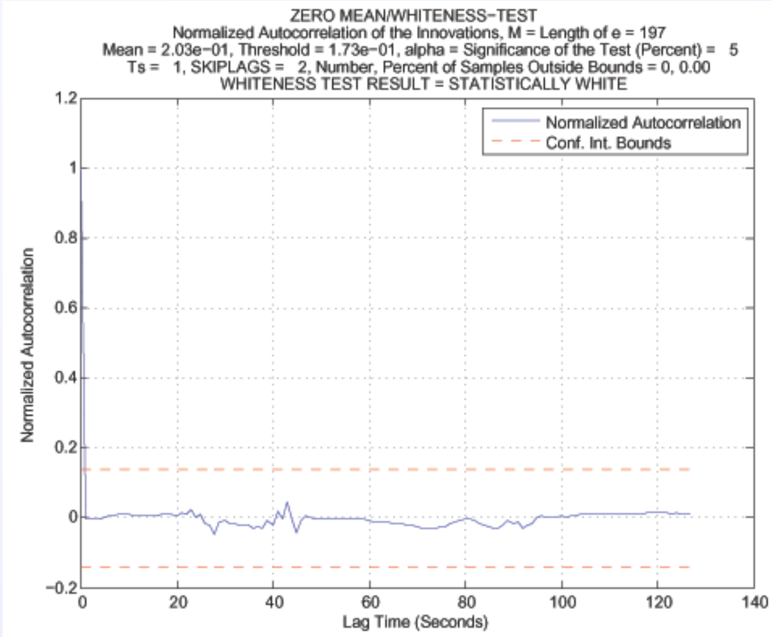


UT1a_WT_euC

System Identification Whiteness Test Result = *White*

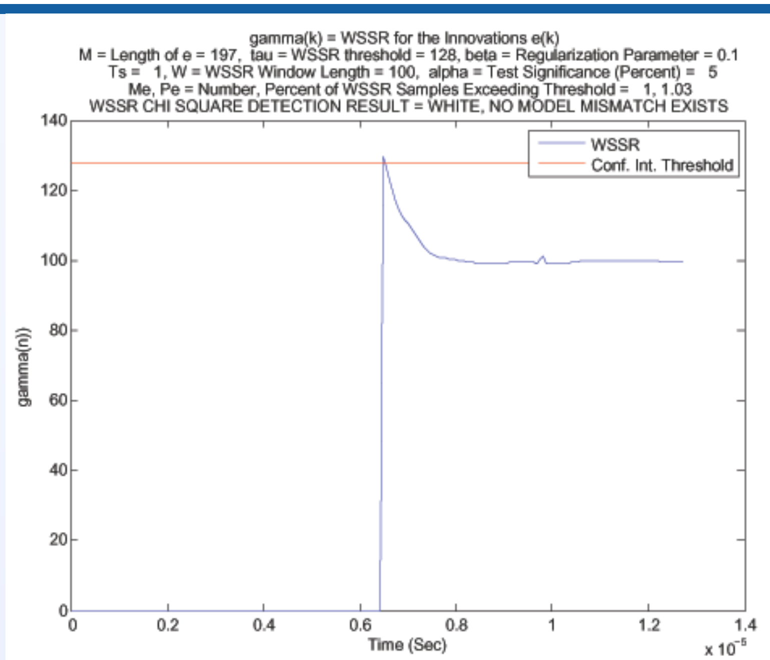
Model:

arx(30,29,1)



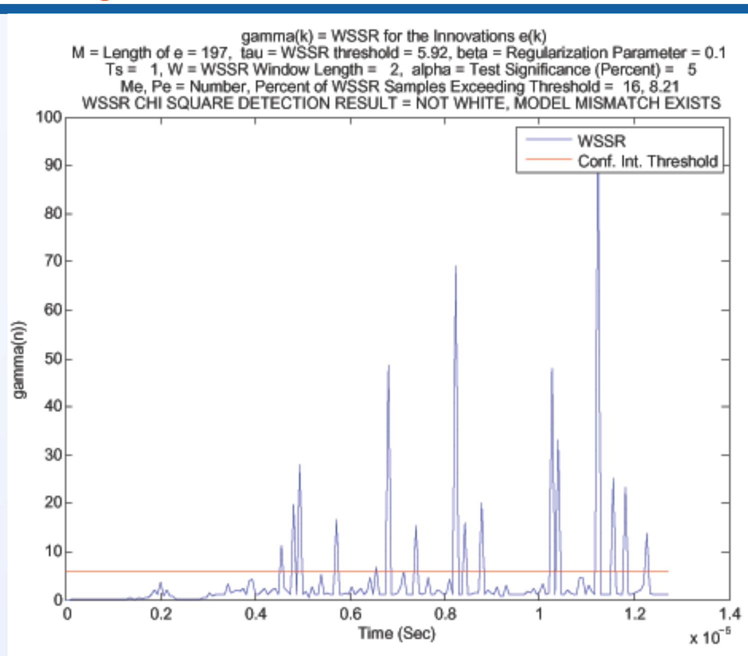
UT1a_WSSR_euC.pdf

System Identification WSSR Test Result = *No Model Mismatch!*



UT1a_WSSR_edC.pdf

"Minor Damage" WSSR Result = *Model Mismatch!*



Conclusions & Future Work

- Basic algorithms were validated with real signals
  - Ultrasonic NDE data
  - TDR data - Receiver Operating Characteristic (ROC) curves and Confidence Intervals

Future Work:

- Receiver Operating Characteristic (ROC) Curves for the Ultrasonic data
- More repeatability studies (test the hardware)
- More controlled experiments with known damage
- More studies with various types of damage
- Compare with other approaches

Contingency VG's

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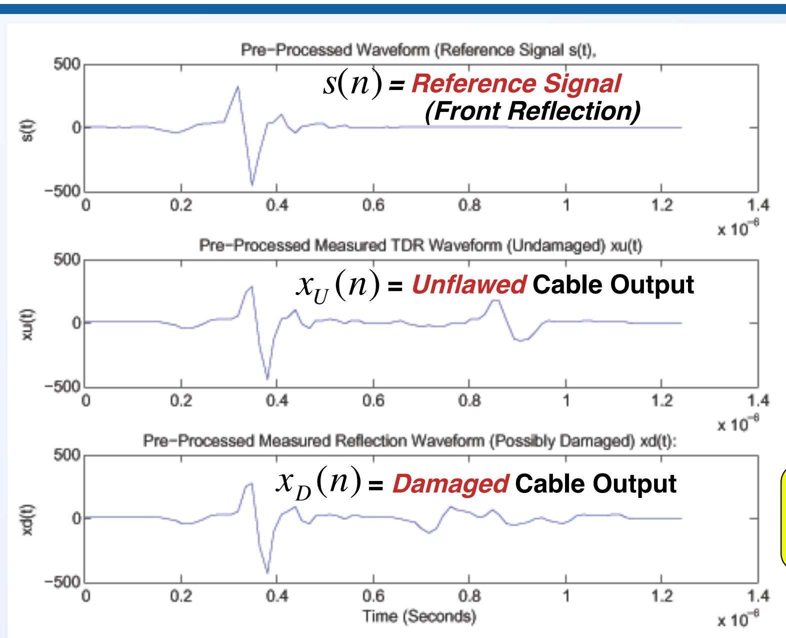
E1_s_xu_xdC.pdf

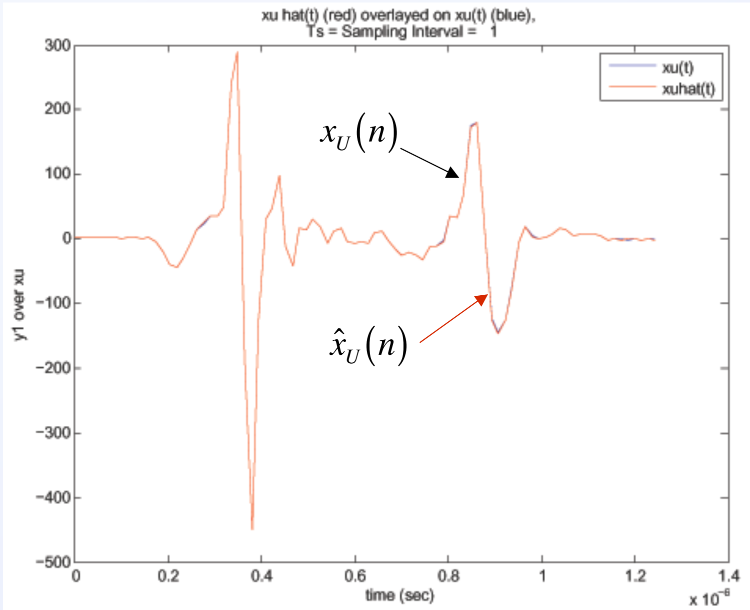
System Identification: Preprocessed Signals



Example: Major Damage

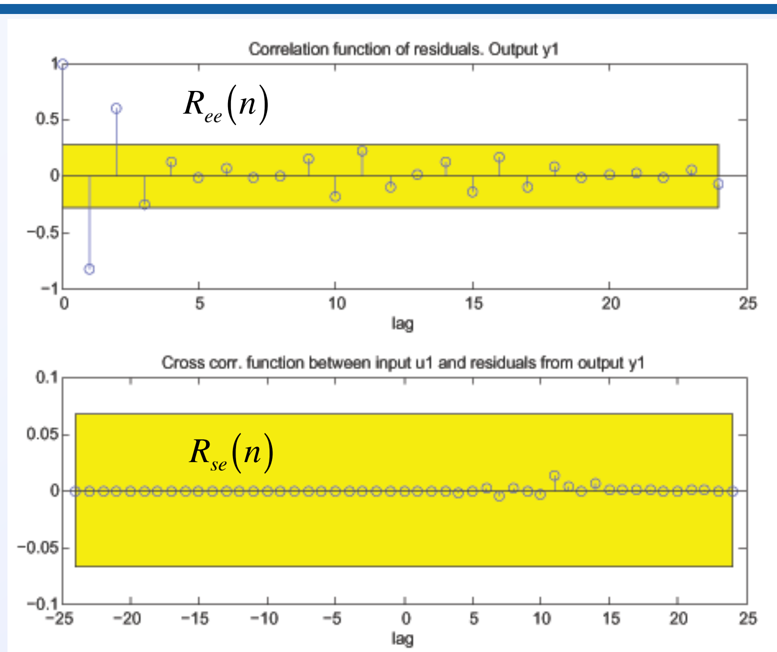
E1_xuhat_xuC.pdf

System Identification: *The Model Fit is Good*



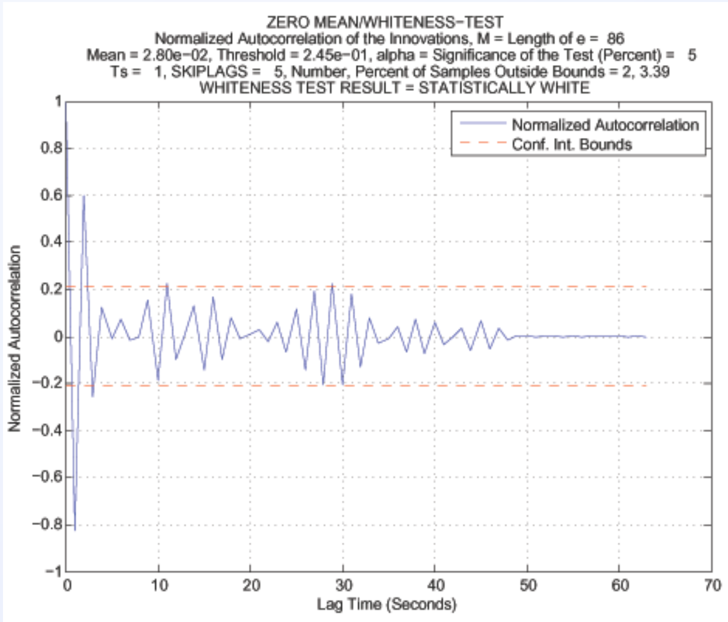
E1_Ree_Rxy1C.pdf

System Identification: *Correlation Tests are Satisfactory*



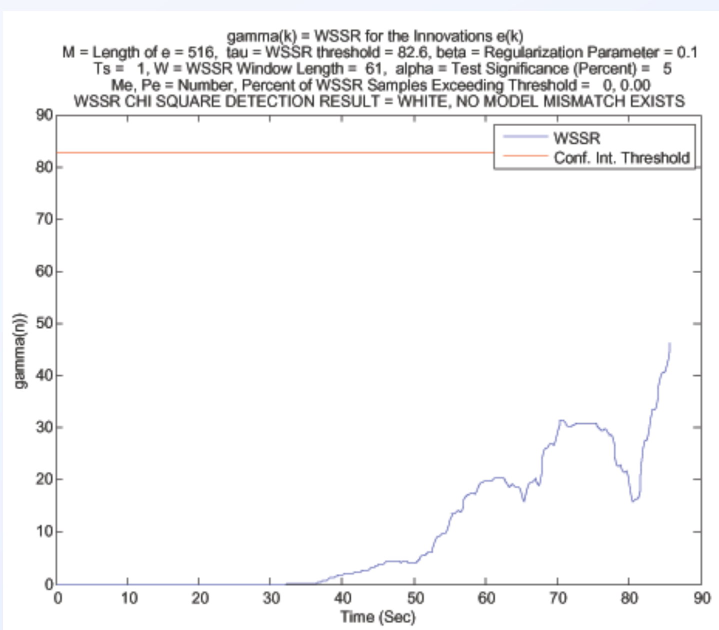
E1_WT_euC.pdf

System Identification Whiteness Test Result = ***White***



E1_WSSR_eu(61)C.pdf

System Identification WSSR Test Result = ***No Model Mismatch!***



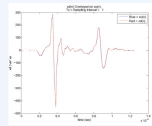
We Acquired an Ensemble of Real Signals for Processing

The PIU was never disconnected between acquisitions *Experiment E1: Data from 2_13_07*

UNDAMAGED

Reference Signals ***(Undamaged):***

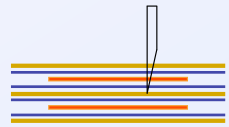
refa, refb, refc



MINOR DAMAGE

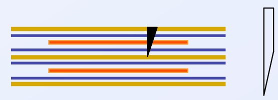
Minor Damage ***(pin hole, knife present, no short):***

minor1a, minor1b, minor1c



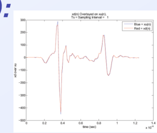
Minor Damage ***(pin hole, knife removed, no short):***

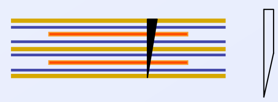
minor2a, minor2b, minor2c



Minor Damage ***(pin hole, knife removed, cable rubbed to remove short):***

minor3a, minor3b, minor3c

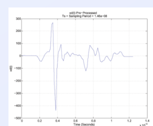


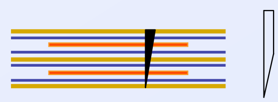


MAJOR DAMAGE

Major Damage ***(pin hole, knife removed, conductors shorted):***

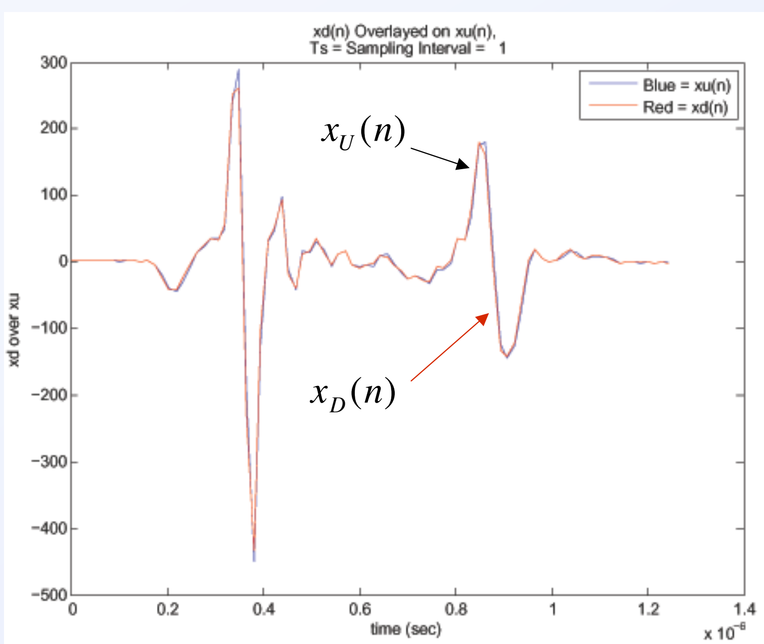
major1a, major1b, major1c





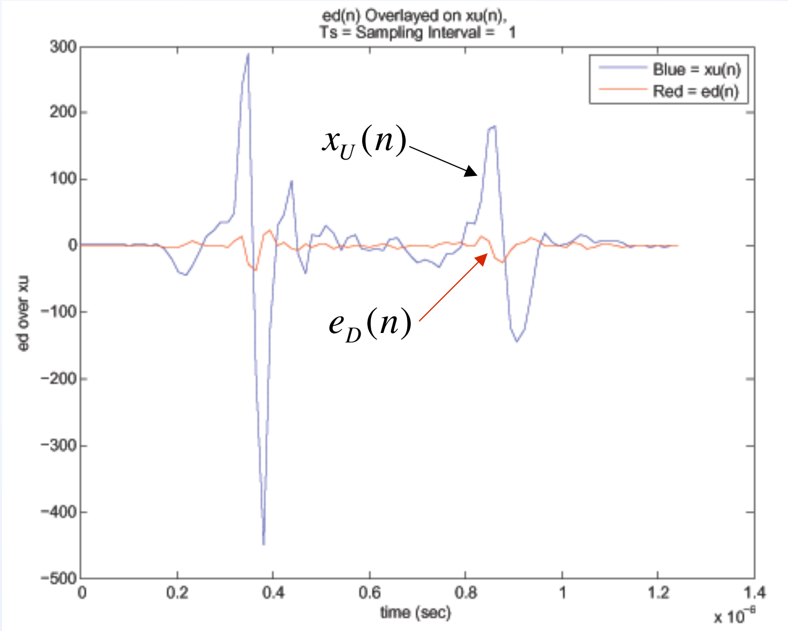
E1_xd_m3a_xuC.pdf

"Minor3 Damage": *Damage Is Difficult to Distinguish Visually*



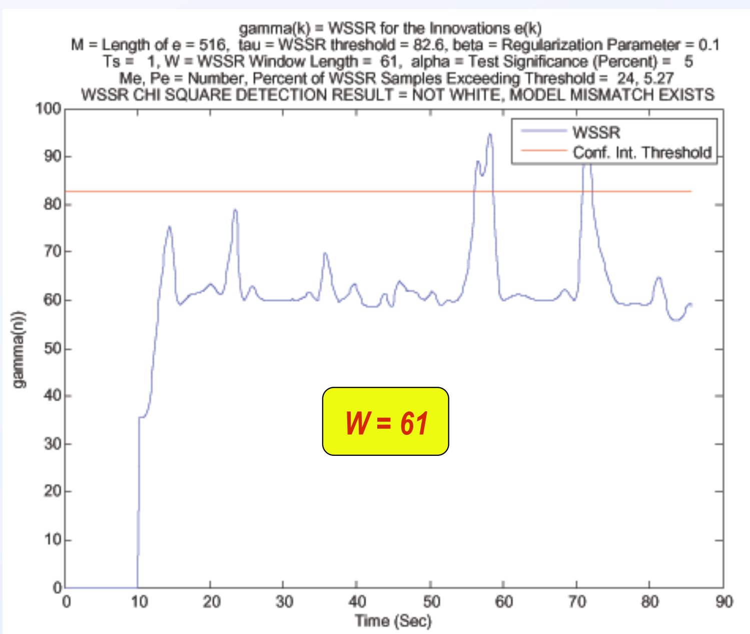
E1_ed_m3a_xuC.pdf

Minor3 Damage: *The Innovations are Small, But Correlated*



E1_WSSR_ed_m3a_(61)C.pdf

"Minor3 Damage" WSSR Result = *Model Mismatch!*



Minor3a,b,c Damage

Receiver Operating Characteristic (ROC) Curve = Perfect

W	P_{FA}	P_D
24	1	1
36	0.66667	1
48	0.66667	1
49	0.66667	1
50	0.66667	1
51	0.66667	1
52	0.66667	1
53	0.66667	1
54	0.66667	1
55	0.66667	1
56	0.33333	1
57	0.33333	1
58	0.33333	1
59	0.33333	1
60	0	1
61	0	1
62	0	0.66667
70	0	0
80	0	0

Probability of Detection vs. Probability of False Alarm